SOIL QUALITY INDICATORS:
A REVIEW WITH IMPLICATIONS FOR AGRICULTURAL ECOSYSTEMS IN ALBERTA

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ALBERTA ENVIRONMENTALLY SUSTAINABLE AGRICULTURE
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EXECUTIVE SUMMARY

Soil quality is a judgement of a soil's ability to provide desired outcomes. For agricultural soils, Acton and Gregorich (1995) provide a practical definition of soil quality as "the soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment". Evaluation of agricultural soil quality is difficult. Agricultural soils are not only important for supporting crop production, now and in the future, but also for maintaining clean water and air, reducing greenhouse gas emissions, preserving natural biodiversity and ensuring food quality. Adding to the difficulty, outcomes of soil functions are not only affected by soil properties, but also by climate, landscape and management; relations among these variables are complex.

Considerable efforts have gone into the development of indicators for soil quality. Indicators communicate correct and relevant information quickly and easily to people who are not necessarily experts in the field. Indicators might be based on a simple relationship between observation and information needs, e.g., a fuel gauge. Indicators might also be based on a proxy relationship between observation and information needs, e.g., the "canary in a coalmine." Indicators might be based on many measurements related to the information needed, e.g., gross domestic product. When expressed relative to an agreed standard, indicators are often referred to as indices, e.g., greenhouse gas index, consumer price index.

Indicators of soil quality were initially developed to provide information on the suitability and relative value of land for different types of agricultural production. More recently, indicators have been developed to provide information on the impacts of agricultural practices on land and environmental degradation. Indicators have also been developed to provide an integrated assessment of soil conditions in programs that monitor a wide range of soil properties. No indicator of soil quality is suitable for all purposes and contexts.

One purpose for a soil quality indicator is communicating information on potential impacts of a change in land management on the outcomes of soil functions. Current indicators for land suitability or relative productivity could be used, but they require modification to increase their sensitivity to objectives other than crop productivity, and possibly to account for soil properties that are unavailable from soil survey databases. Useful approaches for objectives other than crop productivity could be obtained from indicators developed for monitoring land and environmental degradation. Detailed monitoring of soil properties is useful for the validation of soil quality indices. A soil quality indicator based on detailed monitoring of soil properties could also be developed, but would need to be based on clear objectives for soil functions and a sufficient understanding of the linkages between measured soil properties and soil functions.

The following steps are recommended for the development of soil quality indicators useful for monitoring impacts of a change in land management: 1) identify and involve end users, 2) formulate appropriate goals for desired outcomes of soil functions, 3) understand and describe the most important variables and relationships controlling outcomes, 4) assemble a relevant database of observed outcomes and controlling variables, 5) test candidate indicators for scientific soundness, reliable prediction and usefulness, and 6) aggregate indicators for different goals.

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1.0 Introduction

Is soil quality being maintained or enhanced in agricultural ecosystems of Alberta? This question has a long pedigree on the Canadian prairies: J. Bracken observed in 1912 that the essential challenge for prairie agriculture was “finding for each soil and climatic zone the system that is at once the most profitable and the most permanent” (citation from Janzen 2001). This mindset led to the establishment of long-term cropping system experiments by the Dominion Department of Agriculture in the early 1900s. Data obtained over decades and centuries from the different cropping systems studied help to determine the long-term effects of agricultural practices on soil quality and production.

Efforts to maintain or improve prairie soil resources have continued with time. The onset of the Great Depression, or Dirty Thirties, in 1928 began a ten-year cycle of severe drought. Dust storms, soil erosion and crop failure characterized the era, and led the federal government to pass the Prairie Farm Rehabilitation Act in 1935 to preserve the soil resource. Land unsuitable for growing crops was taken out of cultivation and developed as grazing land or community pastures, which are still maintained today (Prairie Farm Rehabilitation Administration 2000). In the 1960s and 1970s, a comprehensive survey of land capability for agriculture, forestry, recreation and wildlife showed that only 5% of Canada’s lands could support annual crop production (Canada Land Inventory 1970). In the 1990s, concerns about soil quality were driven by recognition that soil not only supports agricultural productivity, but also provides important ecological services such as regulating water flow, maintaining clean air and water, and holding and breaking down toxic wastes (Acton and Gregorich 1995).

However, the concept of soil quality is being strongly debated in the professional literature at the present time. Some practitioners endorse research and management of soil quality (Karlen et al. 2003), while others have serious reservations about the validity and application of the concept (Letey et al. 2003). Therefore, as a starting point for this review, a survey of literature related to soil quality indicators was conducted for the AESA Soil Quality Program by Connie Hall of Alberta Agriculture, Food and Rural Development (Hall 2003). The objectives of this review are to evaluate the definitions and goals associated with the soil quality concept, to review approaches used to develop soil quality indicators, and to make recommendations for developing soil quality indicators for agroecosystems in Alberta.

2.0 Definitions and Objectives for Soil Quality

Concerns about soil quality stem from three major issues in agriculture:

1) Are the land resources required for continued agricultural productivity being maintained?
2) Are agricultural lands harming the environment (water quality, air quality, biodiversity)?
3) Are agricultural products safe and nutritious?

Soil properties have a role in all of these goals (Table 1). For example, soil nutrient levels affect crop yield, nutrient leaching and crop composition. The multiple roles of soil have resulted in several broad definitions of soil quality. Acton and Gregorich (1995) defined soil quality as “the soil's fitness to support crop growth without resulting in soil degradation or otherwise harming the environment". Larson and Pierce (1994) stated that "soil quality describes how effectively soils: 1) accept, hold, and release nutrients and other chemical constituents; 2) accept, hold, and release water to plants, streams and groundwater; 3) promote and sustain root growth; 4) maintain suitable biotic habitat; and 5) respond to management and resist degradation". Karlen et al. (1997) defined soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation."

Table 1. Categorization of general goals for agroecosystems.

Goal type	**General goal**	**Key controlling variables**
Economic viability	High productivity	Genetic potential, weather, soil, management, economics
	Low cost of production	Yield potential*, input requirements*, input costs
	Low production risk	Market variation, production variation*
Stewardship	Preservation of productive land	Soil, climate, management
	Healthy animals	Feed quantity and quality*, disease
	High quality food and fiber	Chemical or microbial contamination*, composition*
Social	Viable local communities	Population size, economic viability, economic diversification
	Viable industry, institutions, and infrastructure	Profitability, size and resilience of industry
Environment	Clean water	Climate, soil, management
	Clean air	Climate, soil, management
	Wildlife habitat	Climate, soil, management

*Variables also influenced by soil properties.

More detail is required for the development of useful goals for soil quality. To be useful, goals must be clear and attainable.

A clear goal has measurable criteria that can be used to judge whether the goal has been achieved or not, whereas an unclear goal lacks measurable criteria. In most cases, clear goals also require explicit statements of conditions or constraints required for the achievement of the goal. For example, a goal related to the fitness of a soil to support crop growth needs to control for the effects of crop type, management practice and climate, and may be constrained by self-imposed or mandated limits to environmental impact. Finally, a clear goal does not contain conflicting criteria. Conflicting criteria are often formulated because more than one goal is important, but the variables controlling the achievement of multiple goals are negatively correlated (Dörner 1996). Labelling conflicting goals with a single conceptual label makes them easier to discuss, but does not resolve the conflict. Instead, options to resolve conflicting goals include compromising between goals, focusing on just one goal, or redesigning the system to eliminate the negative correlation.

Attainable goals do not mean easily achieved goals, but do imply the formulation of goals that are possible to attain. For example, a goal to increase soil water holding capacity within one year is not attainable for agricultural fields because soil properties can only be changed gradually over a period of many years. Many soil properties are not suitable as the subject of short-term goals; instead, they function as constraints or controlling variables.

For many practitioners using the soil quality concept, the goal for soil quality is simply to maintain or enhance it. Detailed goals with clear criteria and conditions are not formulated. One reason for this is that soil quality is not currently measurable, making it impossible to formulate a clear goal such as "soil quality in 2050 will be equal to or better than soil quality in 2000."

By definition, soil quality can only be evaluated on assessing the outcomes of soil functions, i.e., by comparing 'what the soil does' to 'what the soil is asked to do' (Carter et al. 1997). Desired outcomes depend not only on inherent soil properties, but also on extrinsic factors such as landscape and climate (see below). Thus, land quality may be a better term than soil quality because it reflects the integration of soil, water, climate, landscape and vegetation attributes at scales important to agro-ecosystem goals (Carter et al. 1997). Soil quality might be considered one component of land quality, but soil quality cannot be defined or determined without accounting for land attributes.

The desired outcomes of soil/land functions include at least the following: crop production, clean water, clean air, low greenhouse gas emissions, safe and nutritious food, and preservation of wildlife habitat.

2.1 Crop Productivity Goals

A useful framework for formulation of crop productivity goals is provided by Cook and Veseth (1991). They present "four A's" for wheat productivity that are applicable for all crops: absolute, attainable, affordable and actual yields (Figure 1). The *absolute yield* is the yield possible with no limiting factors except the genetic potential of the crop. This would be equivalent to at least the maximum yields ever recorded. The *attainable yield* is the highest yield possible in any given soil in any given year, i.e., yield is limited by factors that cannot be altered within the given year. These include factors such as water availability, growing-degree days, depth of topsoil, and total radiation. The *affordable yield* is limited by factors that cannot be ameliorated because management solutions are not affordable to the crop producer (value of potential yield gain is less than its cost) or to the larger society (ecological costs are too high). The *actual yield* is the yield harvested in any given field and is limited by factors that were not ameliorated because they were unforeseen or effective solutions were not known or not implemented.

Goals for the soil function of crop productivity could be formulated at the level of attainable or affordable yields. For example, a possible goal might be as follows:

> "Maximum affordable crop yield, as estimated for all of Alberta using x model or statistical method, will be equal or greater in 2100 to that estimated for 2000, assuming crops, management and climate are unchanged."

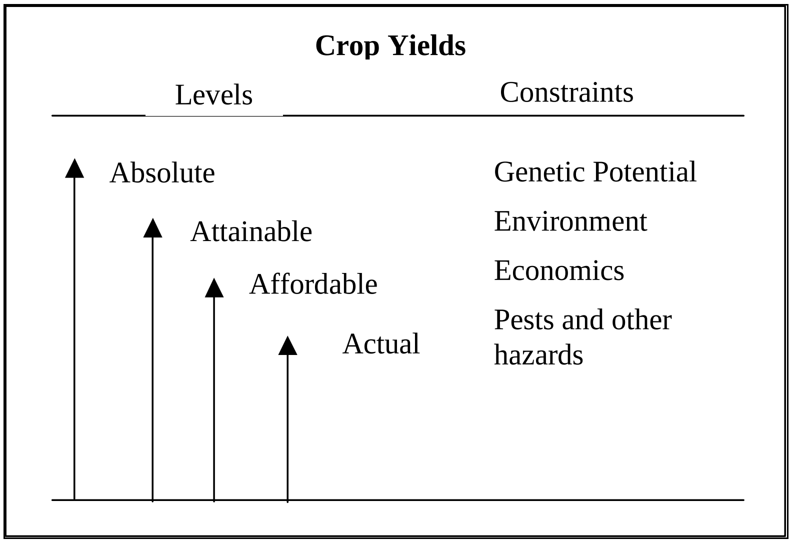

Figure 1. The four A's of crop productivity (modified from Cook and Veseth 1991)

This goal contains criteria and conditions that certainly can be debated and improved upon, in contrast to an unclear goal. Debate and improvement are the first steps in the formulation of useful goals.

2.2 Water Quality Goals

Water quality is a measure of the fitness of water for desired uses, such as drinking water or the health of aquatic ecosystems. The main contaminants reducing water quality in runoff and drainage from agricultural lands are nutrients, suspended solids, fecal coliform bacteria, and pesticides. Contaminant levels in water leaving agricultural soils depend on the ability of the soil to modify water flow and to either retain contaminants or support their removal by the crop. These functions of soil depend on soil properties, soil position in the landscape, land management, weather, and interactions among these factors.

A goal for soil functions related to water quality might be formulated similarly to crop productivity:

> "Quality of water in runoff and drainage from Alberta's croplands will meet x water quality standard in 2050, based on y model or statistical method."

2.3 Air Quality Goals

Air quality is primarily a measure of the purity of air. The main issues in air quality from agricultural lands are particulates and pesticides. Contaminant levels in air leaving agricultural soils depend on the ability of soil to retain soil particles and associated constituents. This function of soil depends on soil characteristics, soil position in the landscape, land management, weather, and interactions among these factors.

Air quality is not widely monitored, but wind erosion is a significant contributor to soil degradation in Alberta and elsewhere, and various models are available and have been tested in Alberta. A goal for soil functions related to air quality might be formulated as follows:

> "Wind erosion from Alberta's croplands will be equal or less in 2050 to that estimated for 2000, based on x model or statistical method."

2.4 Greenhouse Gas Emission Goals

Canada's goal (Kyoto Protocol) is to reduce its average annual emissions of greenhouse gases (GHG) (nitrous oxide, methane and carbon dioxide) for the 2008-2012 period to a level 6% below its greenhouse gas emissions in 1990. Soil is a source and a sink of all of these gases. A goal for soil functions related to GHG emissions might be formulated as follows:

> "Net GHG emissions from Alberta's croplands in the 2008-2012 period will be 6% below that in 1990, based on the Intergovernmental Panel on Climate Change methodology."

2.5 Natural Habitat/Biodiversity Goals

Loss of habitat is among the leading causes of decline in the number and diversity of natural organisms. In general, habitat quality is inversely related to the intensity of land management. For example, cropland generally provides better habitat than developed land, but poorer habitat than native pastures. A goal for soil functions related to habitat might be formulated as follows:

> "No net conversion of land under natural vegetation to more intense agricultural uses in x period in Alberta, based on y methodology."

2.6 Food Quality Goals

There are two sides to food quality. One side is avoidance of harmful constituents in food, such as heavy metals or pathogenic microorganisms (Abrahams 2002). The other side is the achievement of constituents that promote human and animal health, such as desirable levels of micronutrients, protein and energy. Many factors affect food quality. Soil has an impact on food quality through its effects on the availability or mobility of undesirable constituents and through its effects on crop growth. A goal for soil functions related to food quality might be formulated as follows:

> "Composition of food grown on Alberta's agricultural land will meet x food standard, based on y monitoring methodology (e.g., sampling scheme of worst-case scenarios)."

3.0 Models and Information Requirements

Formulation of clear goals provides a destination, but not the route to achieve them. The next step is to gather information and develop a map or model of the factors that control desired outcomes (Figure 2).

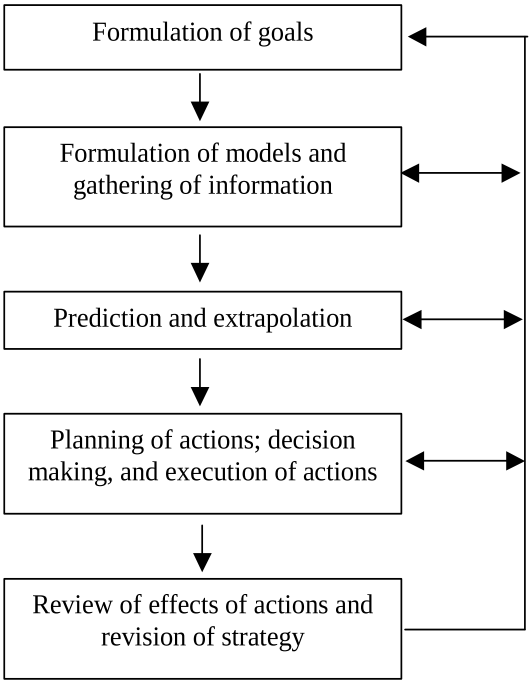

Figure 2. Steps in the organization of complex action (from Dörner 1996, p. 43)

Models are representations of the current understanding of a phenomenon or process of interest (Addiscott 1993; Yaalon 1994). Of necessity, they are simplifications of reality. Three types of models are often recognized. *Stochastic models* describe the relationship among variables using best-fit stochastic coefficients, without consideration of causal relationships. *Functional models* describe the relationship among variables using the simplest description of causal relations possible that still provides a useful description of the process or phenomenon. *Mechanistic models* describe the relationship among variables using only the most elementary description of causal relationships possible. As an example, the braking system of a car can be modelled using each of these approaches (Dörner 1996). A stochastic model would describe the braking system as the relationship between pressure on the brake pedal and deceleration of the car. A functional model would describe the components of the braking system and how they interact to slow the car. A mechanistic model would describe the properties of the materials contained in the components of the braking system. The appropriate description depends on the use. A stochastic model may be sufficient for a driver to operate the car, while a functional model would be required for a mechanic to maintain the braking system and a mechanistic model would be required by an engineer to design improved brake systems.

Gathering information and formulating models are activities that may never be completed, particularly if you are a scientist, due to the infinite depth and detail it is possible to go into. The challenge is to aggregate sufficient information so that reasonably sound action plans can be developed, given the constraints of time and money that limit efforts in this area.

The initial information requirement is identification of the variables controlling outcomes and the interrelationships of these variables. For example, variables controlling the quality of runoff water include precipitation, topography, land cover, and soil nutrients. Information is also required on the *driving forces* that impact the variables controlling *outcomes,* such as the economic forces affecting the choice of tillage system or nutrient application rate. Finally, information is required on the type and effectiveness of *responses* that could be used to achieve goals, such as the use of buffer strips, the maintenance of soil-available nutrients below a specified level, appropriate manure and fertilizer application methods, and development of environmental farm plans. This *driving force-outcome-response* framework (or pressure-state-response framework) is widely used in environmental assessment (e.g., McRae et al. 2000).

Challenges exist even when information is available. System complexity limits our ability to accurately determine the barriers to desired outcomes. Relationships among variables are often non-linear and buffered to various degrees, making it difficult to predict responses. Goals conflict with each other due to negative correlations among variables controlling outcomes. It is also more difficult to achieve multiple goals than simple goals, and multiple goals require more sophisticated solutions. The achievement of goals requires expertise in a large number of subjects.

Complexity is also increased due to the wide range in scale of issues related to soil functions. Scale refers to the time or distance over which a phenomenon exists or cycles (Blöshl and Sivaplan 1995). For example, soil taxa at the level of order or great group exist over distances of hundreds of kilometres and are the product of centuries or millennia of pedogenic processes. In contrast, the soil rhizosphere only exists within a few millimeters of the root surface and undergoes rapid changes within periods of even a few hours. In general, phenomena that occur at large temporal scales also occur at large spatial scales.

The temporal and spatial scales of soil processes extend over ten orders of magnitude (Ellert et al. 1997). These are scales of natural phenomena and beyond our control. In contrast, observations of soil processes can be made at different scales, within limits set by resources and instrumentation. Observation scale is defined by the spatial or temporal extent of sampling (coverage), spacing between samples (resolution), and integration volume of a sample (Blöshl and Sivaplan 1995). Processes that occur at scales larger than the observation scale appear as trends in the data, while processes that occur at scales smaller than the observation scale appear as noise. Modelling represents another activity that can be conducted at different scales. Modelling scale is usually selected based on the scale of the process and the application for which the model is to be used. Finally, management occurs at a range of spatial (field, farm, watershed, ecoregion, etc.) and temporal (seasonal, annual and multi-year) scales.

Potential problems occur when observations and models determined at one scale are used for processes or applications at a different scale. Observations or models obtained at a small scale may be inappropriate to make conclusions at a large scale due to higher level interactions, lack of appropriate data for model validation, high cost of data collection and analysis, and low value of information due to increased complexity (Blöshl and Sivaplan 1995). For example, estimates of the contribution of soil erosion to poor water quality based on estimates of soil erosion from hill slopes may be inaccurate due to factors that control the proportion of soil erosion that enters a watercourse. Observations or models obtained at a large scale may be inappropriate to make conclusions at a small scale due to the difficulty in disaggregating large-scale values. For example, an estimate of soil erosion for a particular field based on regional estimates may be inaccurate because it does not reflect the factors controlling soil erosion in that particular field.

4.0 Indicators

The next step after obtaining a sufficiently accurate map or model of barriers to goals is to develop and implement plans to achieve goals (Figure 2). It is useful at this stage to develop indicators to guide progress toward the goal and to detect if improvements in goals, models or action plans are required.

What are indicators? Indicators are representations that communicate correct and relevant information quickly and easily to people who are not necessarily experts in the field (Jesinghaus 1999). In contrast, data are values that need further processing before they provide meaningful information, such as a statistic. Statistics describe real phenomena according to exact definitions, but they often require interpretation. Indicators communicate a correct message without further interpretation (note: the term ‘indicator’ is also used generically for any variable related to the information of interest).

Indicators may be based on a simple relationship between observation and information needs, e.g., a fuel gauge. Indicators might also be based on a proxy relationship between observation and information needs, e.g., the “canary in a coalmine”. Finally, indicators might be based on many measurements related to the needed information, e.g., gross domestic product. When expressed relative to an agreed standard, indicators are often referred to as indices, e.g., greenhouse gas index, consumer price index.

Indicators of soil quality should communicate how well goals related to soil functions are being achieved (Figure 3). At the same time, they are also effective for the communication of goals and knowledge related to soil functions.

Good indicators are relevant, sound and cost-effective. A relevant indicator is directly related to the most important aspects of the goal, is self-explanatory, is sufficiently sensitive for its purpose, and can be used to develop and monitor actions. A sound indicator is acceptable to experts in the field, regardless of their backgrounds. Thus, it is science-based and sufficiently accurate, precise and robust for its intended purpose. For an indicator to be cost-effective, the value of its information must be greater than its cost. In general, this means required data is readily available, computation is relatively easy, and the data is required or synergistic with other needs.

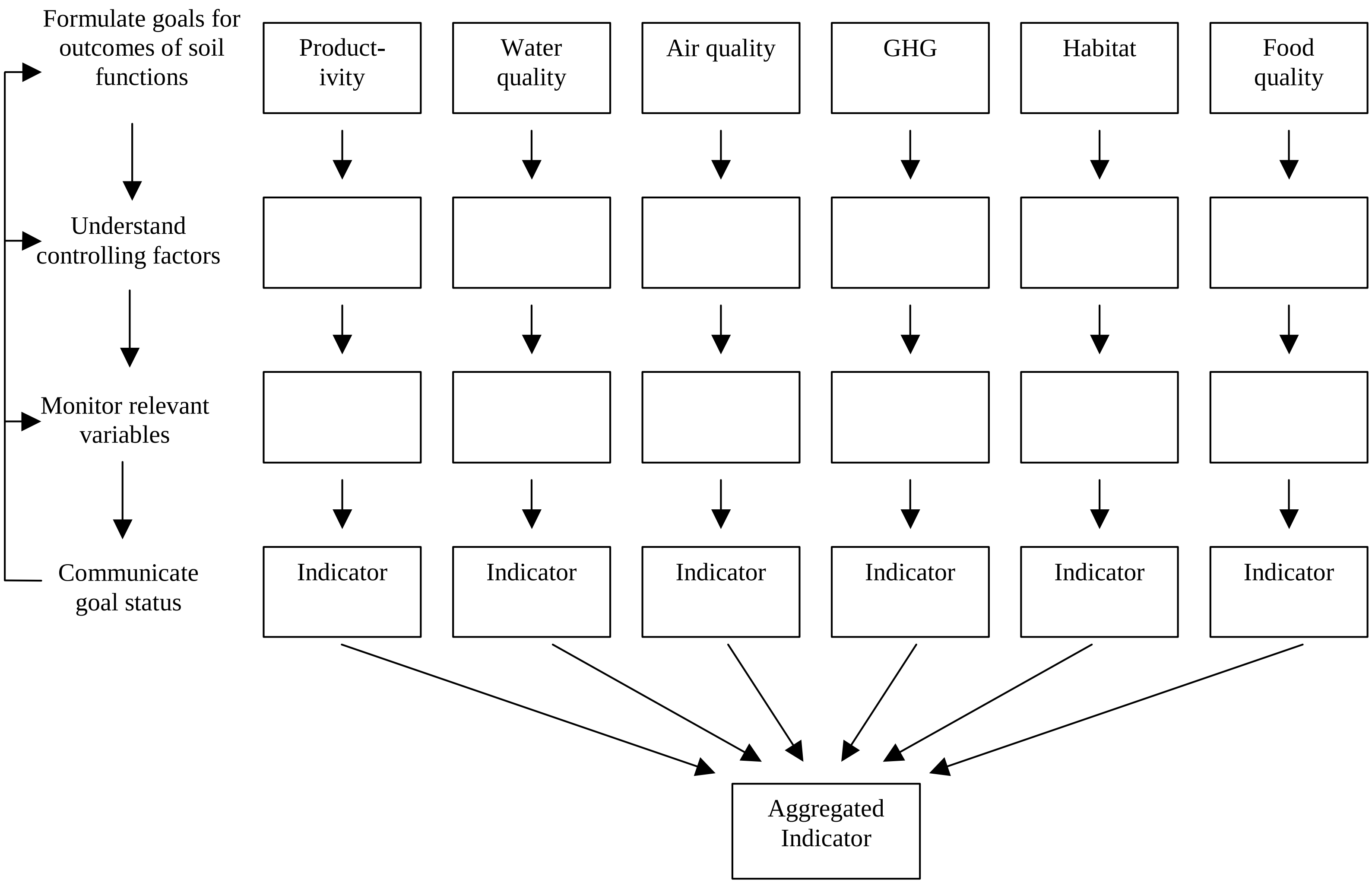

Figure 3. Proposed flowchart for the evaluation of soil quality

Indicators can be used to communicate information on driving forces, outcomes, or responses. Driving force indicators communicate information on the causes of a problem, which may provide incentives for appropriate responses or be used to monitor the efficacy of responses. Outcome indicators communicate information on the effects of a problem on a goal. Outcome indicators are often slow to respond, but are directly related to the issue and are useful for assessment and planning. Response indicators communicate information on the extent to which remedial actions are implemented. Response indicators respond quickly, but their effects are not evident until much later.

Indicators may communicate information on level, change or structure (Garcia 1997). An indicator of *level* provides an absolute measure of driving force (e.g., market price of annual crops), outcome (e.g., area of unsuitable land under annual cropping) or response (e.g., area of unsuitable land with regulations prohibiting annual cropping). An indicator of *change* provides information on the direction and rate of change in driving force (e.g., change in market prices), outcome or response. An indicator of *structure* provides information on industry or policy structures related to driving force (e.g., average farm size) or response (e.g., proportion of farms with an environmental farm plan).

5.0 Indicators of Soil/Land Quality – Examples

The following examples provide an overview of the history and approaches of soil and land quality assessment. They are not a comprehensive list of all efforts in this area.

5.1 United States

The Land Capability Classification represents one of the earliest systems of land quality assessment (Helms 1992). The purpose of this classification system was to provide farmers and government agencies with a tool to determine land that was capable of supporting permanent agriculture, particularly with respect to potential soil erosion. The system consists of eight categories ranging from class 1 soils that have little or no limitations restricting their use for crop production, to class 8 soils that cannot be used for commercial crop production. Four letters are used as subclasses to represent the major hazard or limitation that contributes to the soil occurring within the capability class: (e) erosion, (w) excess wetness, (s) problems in the rooting zone, and (c) climatic limitations. Inputs for the classification system are based on properties that cannot be altered due to technical or economic constraints and include landscape location, slope of the field, depth, texture, reaction of the soil, climate, erosion and risk of flooding. Criteria for classification are somewhat subjective due to the flexibility required for the wide range of cropping systems, climates and soils present in the United States (Davidson 2002).

The classification was applied at the national scale during survey efforts conducted from the 1930s through the 1950s (Helms 1992). The originators of the system realized their land classifications were not permanent and a reappraisal might be necessary due to changes in the land or cropping practices. They hoped "merely to establish a national basis of classification which would be good for a generation or two" (E.A. Norton 1940, as cited by Helms 1992).

Due to environmental concerns, the National Resources Inventory (NRI) was developed to provide a statistically robust survey of natural resource conditions and trends on non-federal land in the United States (Nusser and Goebel 1997). The NRI was conducted in 1977 for the first time, then every five years until 1997. Data have been collected every year since 2001, but for slightly less than 25% of the same sample sites (NRCS 2003). Prior to 2001, data were collected from about 800,000 sample sites contained within 300,000 primary sampling units. Primary sampling units consist of 40 to 160 acre land segments. In a typical county, two primary sampling units (160 acres) are selected for each 6 x 2 mile area, an approximate 4% sampling rate (Nusser and Goebel 1997).

Three sample points are typically obtained within each primary sampling unit (Nusser and Goebel 1997). At each sample point, information is collected on variables such as land cover/use, soil classification, soil properties, erosion factors and related information. For each primary sampling unit, information is collected on climate factors, urban areas, water bodies and related information. Data are collected using photo-interpretation and remote-sensing methods or from available databases (e.g., climate, soil survey), USDA field office records and local NRCS personnel (NRCS 2003). All sample sites were field visited in 1982, about one quarter of sample sites were field visited in 1992 (Nusser and Goebel 1997), and sites where aerial photography was unavailable or unsuitable were visited in 2001 (NRCS 2003). Results are presented for a number of issues relevant to soil functions:

Erosion: for all sample points, water erosion is estimated by the Universal Soil Loss Equation (USLE) and wind erosion is estimated by the Wind Erosion Equation (WEQ). Estimates of both types of erosion (total tons of soil eroded per year, tons eroded per acre, total acres with erosion greater than tolerable, etc.) are available for cropland at the national, state and sub-state scales since 1982.

Urbanization: conversion of all types of rural land (prime farmland, cropland, grazing land, etc.) to developed land is available for cropland at the national, state and sub-state scales since 1982.

Water quality: watersheds with the greatest risk of non-point pollution are identified based on leaching and runoff vulnerability indices calculated for pesticides and nutrients. For example, vulnerability indices for nutrients are obtained from estimates of excess nutrient levels (manure or commercial fertilizer sources) combined with estimates of leaching (based on precipitation and hydrologic factors) or estimates of runoff (based on precipitation and USLE curve numbers) (Kellogg et al. 1997).

Soil quality: Future Annual NRI results will present long-term trends of a Soil Condition Index value for each NRI sample site (NRCS 2003). The Soil Condition Index quantifies the effects of cropping sequences, tillage and other management inputs on trends in soil organic matter content, which will be used as an indicator of soil quality. Climate and soil data will also be used in the assessment.

In addition to these efforts conducted at a national scale, efforts to derive meaningful representations of specific or multiple soil functions have occurred at state and regional scales. One of the early motivations for soil ratings was equitable tax assessment. Huddleston (1984) provides a thorough review of the development and use of soil productivity ratings in the United

States until the early 1980s. In general, relative rating systems based on relations to soil and climatic properties were preferred due to the lack of sufficient yield data for different soil types. Rating systems aggregate variables controlling yield outcomes by the use of multiplication, addition or a combination of the two. For example, the Storie Index Rating is determined by multiplying together separate ratings for profile morphology, surface soil texture, or slope, and modifying factors, such as depth, drainage, or alkalinity. Rating systems have successfully estimated productivity for soils lacking yield data, provided the rating systems were adequately validated for the conditions in which they were used. Huddleston (1984) concluded the following steps should be used to derive soil productivity ratings:

- Assignment of numerical values to all soil properties, landscape characteristics and weather conditions that influence plant growth and yield
- Use of both additive and multiplicative processes to formulate factor ratings and combine factors into final productivity ratings
- Use of available yield data, either directly or indirectly, to develop and validate the ratings
- Precise specification of all criteria used to assign numerical values, derive factor ratings, and combine factors in the model

Another motivation for soil assessment was an interest in quantifying the economic benefits and sustainability of conservation measures (Pierce et al. 1983; Popp et al. 2002). Pierce et al. (1983) estimated the impact of soil erosion on crop productivity using a soil productivity index modified from Kiniry et al. (1983). The approach used in these studies was to estimate the sufficiency of soil conditions for root growth, relative to that expected in an ideal soil:

$$\mathrm{PI} = \sum_{i=1}^{r} (A_i x C_i x D_i x WF_i)$$

where PI is productivity index, A_i is sufficiency of available water capacity, C_i is sufficiency of bulk density, D_i is sufficiency of pH, WF_i is weighting factor for each horizon and r is the number of horizons in the depth of rooting. A reasonable fit was obtained with corn yields in Minnesota for several soil series (Pierce et al. 1983). Using this equation, Pierce et al. (1983) showed that certain subsoil characteristics caused some soils to be more vulnerable than others to loss of crop productivity due to soil erosion. Popp et al. (2002) modified the above equation by adding a term representing the sufficiency of organic matter. Based on expected differences in soil quality among several soils with different conservation practices and comparison to yields determined using the EPIC (Erosion-Productivity Impact Calculator) model, they concluded their soil quality indicator outperformed the index by Pierce et al. (1983).

Since the early 1990s, there has been a considerable effort in the United States to develop soil ratings based on measured soil properties for the comparison of land management systems (Karlen et al. 2001). In this approach, soil quality is considered an inherent property of the soil that can be determined from measurable soil attributes (Larson and Pierce 1994). When a soil quality parameter declines below an acceptable limit, an appropriate response is required to increase soil quality. Acceptable limits depend on land use, soil characteristics, landform and climatic conditions.

Many potential parameters of soil quality, measurable at various scales of assessment, have been proposed (Table 2). In a 10-year study of crop residue effects conducted in Wisconsin, a soil quality index was estimated by weighting factors related to water infiltration (aggregate stability, surface porosity), water absorption (porosity, total C, earthworms), degradation resistance (aggregate stability, microbial processes) and plant growth (parameters affecting rooting depth, water relations, nutrient relations and acidity) (Karlen et al. 1994).

Table 2. Potential biological, chemical, and physical indicators of soil quality, measurable at various scales of assessment (from Karlen et al. 2001).

Biological	Chemical	Physical
	Point-scale indicators	
Microbial biomass	pH	Aggregate stability
Potential N mineralization	Organic C and N	Aggregate size distribution
Particulate organic matter	Extractable macronutrients	Bulk density
Respiration	Electrical conductivity	Porosity
Earthworms	Micronutrient concentrations	Penetration resistance
Microbial communities	Heavy metals	Water-filled pore space
Soil enzymes	CEC and cation ratios	Profile depth
Fatty acid profiles	Cesium-137 distribution	Crust formation and strength
Mycorrhiza populations	Xenobiotic loadings	Infiltration
	Field-, farm-, or watershed-scale indicators	
Crop yield	Soil organic matter changes	Topsoil thickness and color
Weed infestations	Nutrient loading or mining	Compaction or ease of tillage
Disease pressure	Heavy metal accumulation	Ponding (infiltration)
Nutrient deficiencies	Changes in salinity	Rill and gully erosion
Growth characteristics	Leaching or runoff losses	Surface residue cover
	Regional-, national-, or international-scale indicators	
Productivity (yield stability)	Acidification	Desertification
Species richness, diversity	Salinization	Loss of vegetative cover
Keystone species and ecosystem engineers	Water quality changes	Wind and water erosion
Biomass, density and abundance	Air quality changes (dust and chemical transport)	Siltation of rivers and lakes

An adapted form of the index from Karlen et al. (1994) was used to evaluate the soil quality from an 8-year tillage study in southern Illinois (Hussain et al. 1999). Based on soil samples obtained from 36 farm fields under conventional tillage, no-tillage and non-disturbed management, Wander and Bollero (1999) concluded that particulate organic matter, mean wet weight diameter of aggregates, bulk density and penetration resistance may be good indicators of soil quality because they are sensitive to management and environmentally relevant.

Islam and Weil (2000) concluded that total microbial biomass, active microbial biomass and basal respiration per unit of microbial biomass showed the most promise for inclusion in an index of soil quality, based on soil samples of contrasting management systems obtained from long-term replicated field experiments and pair field samples in mid-Atlantic states. Brejda et al. (2000) found that the most sensitive indicators of soil quality among land uses were total organic C and total N in the Central High Plains, and total organic C and water stable aggregate content in the Southern High Plains. Andrews et al. (2002) calculated a soil quality index based on bulk density, DTPA-extractable Zn, water stable aggregates, pH, electrical conductivity and soil organic matter in an on-farm study with various organic amendments in California's Central Valley.

Other examples of the development and use of soil quality indices are provided by Karlen et al. (2001), who concluded that there is no ideal or universal index for soil quality. Rather, utilization of the soil quality concept requires that the following steps be followed (Figure 4):

- Identify critical functions
- Select appropriate indicators
- Develop appropriate scoring or interpretation guidelines
- Combine the information into index values to determine if the resource is being sustained, degraded, or aggraded.

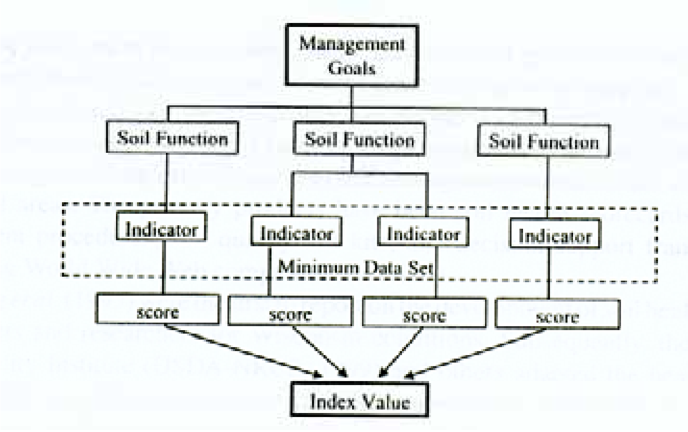

Figure 4. A generalized framework for developing soil quality indices (from Karlen et al. 2001)

5.2 Canada

The Canada Land Inventory (CLI) was established in 1963 to provide a comprehensive survey of land capability for the purposes of agriculture, forestry, recreation and wildlife (Canada Land Inventory 1970). The Soil Capability for Agriculture (SCA) classification system is similar in approach to the Land Capability Classification system in the United States. It is an interpretative system based on expert knowledge that classifies soils into seven classes based on their suitability for sustained production of annual field crops (Canada Land Inventory 1965). Class 1 soils are the most suitable (least limitations) for sustained production of annual field crops, while Class 7 soils are unsuitable (most limitations) for sustained production of annual field crops.

Classes 1 to 3 are deemed capable of sustained production of annual field crops, while Classes 4 to 6 are recommended for different agricultural uses, such as perennial forage crops, improved pasture and native grazing. Limiting factors included in the classification system include climate (temperature and precipitation), soil structure and/or permeability, erosion, fertility, pH, depth to consolidated bedrock, topography, stoniness, salinity, and risk of flooding, drought or excess water. The inventory was assessed at a large spatial scale (1:30,000+) with limited resolution at local scales. The inventory was designed to be valid for a long time period, although it was recognized that changes in class ratings would occur due to land improvement or degradation. The SCA classification system reflects actual land use, which may serve as one type of validation for the system. In southwestern Ontario, the SCA classification system was significantly correlated with gross returns and gross margin per acre for grain corn production (Patterson and Mackintosh 1976).

The Land Suitability Rating System (LSRS), a revised version of the SCA classification system, was developed in 1995. The LSRS was designed to be more quantitative and better documented, and to encompass organic as well as mineral soils (Agronomic Interpretation Working Group 1995). The overall framework and class ratings from the SCA classification system are preserved, but rating factors are specified for spring-seeded small grain crops (wheat, barley, oats); other crops may be included in the future. The LSRS estimates the suitability of land for crops based on separate ratings for climate, soil, and landscape. Ratings for each component may range from 0 to 100, and the overall land rating is simply the lowest of the three ratings.

Pettapiece et al. (1998) used the LSRS in a pilot project to estimate possible changes in soil quality due to soil erosion or organic matter depletion. Changes in soil properties were estimated from 30-year simulations of EPIC for various combinations of soil landforms, crop rotation, tillage intensity and climate in 15 ecodistricts in Alberta. The project allowed assessment of soil quality trends at regional scales.

The Agri-Environmental Indicator Project developed indicators of the environmental sustainability of Canadian agriculture (McRae et al. 2000). Many of the indicators developed as part of this project are directly or indirectly related to soil quality (Table 3). Indicators are calculated by integrating information on soil, climate, and landscape from *Soil Landscapes of Canada* polygons with information from the *Census of Agriculture* and custom data sets (from provincial agencies, the private sector and other sources). The information is integrated using existing or modified mathematical models selected or developed by scientists and analysts with expertise in the subject. For example, the risk of soil erosion by water is estimated using the Revised Universal Soil Loss Equation, with land use and tillage practice information obtained from the *Census of Agriculture*, and rainfall, soil and slope characteristics obtained from *Soil Landscapes of Canada* and other sources. Indicators are calculated once every five years based on the availability of *Census of Agriculture* data. Most indicators are calculated at the soil polygon scale (3123 soil polygons), and are aggregated to ecodistrict (386), ecoregion (70) and ecozone (7). In some cases, indicators could only be calculated at the provincial or ecozone scale. The indicators are best suited to communicate information of broad changes in environmental impacts over time and among regions.

Table 3. Canadian agri-environmental indicators (from McRae et al. 2000).

Indicator Group	**Agri-environmental indicator**	**Description**	**Frame-work Element**	**Coverage**
Environ-mental Farm Management	Soil Cover by Crops and Residue	Number of days per year when soil is left exposed under specific crop and land management regimes.	Driving Forces Response	National
	Management of Farm Nutrient and Pesticide Inputs	Adoption of best management practices for handling fertilizer, manure, and pesticides.	Driving Forces Response	National
Soil Quality	Risk of Water Erosion	Potential for soil loss in surface runoff under prevailing landscape and climatic conditions and management practices.	Outcome	National
	Risk of Wind Erosion	Potential for soil loss under prevailing landscape and wind conditions and management practices.	Outcome	Prairie Provinces
	Soil Organic Carbon	Estimate of change in organic carbon levels in soils under prevailing management practices.	Outcome	National
	Risk of Tillage Erosion	Potential for soil redistribution under prevailing landscape conditions and tillage and cropping practices.	Outcome	National
	Risk of Soil Compaction	Potential for change in degree of compaction of clay-rich soils estimated from inherent soil compactness and cropping system.	Outcome	Ontario, Maritime Provinces
	Risk of Soil Salinization	Potential for change in the degree of soil salinity estimated from land use, hydrologic, climatic, and soil properties.	Outcome	Prairie Provinces
Water Quality	Risk of Water Contamination by Nitrogen	Potential for nitrogen levels in water leaving farmland to exceed Canadian drinking water standard.	Outcome	Humid Ecozones
	Risk of Water Contamination by Phosphorus	Potential for phosphorus to move off farmland into surface waters.	Outcome	Quebec
Agroeco-system GHG Emissions	Agricultural Greenhouse Gas Budget	Estimated emissions of nitrous oxide, methane, and carbon dioxide from agriculture production systems; summary balances expressed in carbon dioxide equivalents.	Outcome	National
Agroeco-system Biodiversity	Availability of Wildlife Habitat on Farmland	Number of habitat-use units for which habitat has increased, remained constant, or decreased.	Outcome	National
Production Intensity	Energy Use	Energy content of agricultural inputs and outputs.	Driving Forces	National
	Residual Nitrogen	Difference between the amount of N added to farm soils and the amount removed in harvested crop.	Driving Forces	National

5.3 New Zealand

In New Zealand, soil quality indicators were developed to meet an environmental requirement to monitor potentially detrimental effects of human activities on the environment (Sparling and Schipper 2002). Environmental requirements are the responsibility of 17 autonomous regional authorities since the Resource Management Act was passed in 1991. Efforts to monitor soil health were initiated in the late 1990s to augment the monitoring of soil erosion that was being conducted by most of the regional authorities. The goal for the program is the use, by 2010, of critical thresholds of soil quality indicators and an associated monitoring system at the regional scale (Manaaki Whenau Landcare Research 2004).

The objective of the program is to monitor the soil quality of 500 soils distributed throughout New Zealand using a three-year sampling frequency (Manaaki Whenau Landcare Research 2004). Soil selection is based on a combination of soil type and land use, and on the perceived risk of soil type/land use to the environment (Sparling and Schipper 2002). Soil type is based on the New Zealand classification of soil order, and 12 of the 15 soil orders are included in the initial sampling program. Land use is divided into nine categories including cropland (arable and mixed), pasture (three types), orchards, grassland, plantation forest and indigenous vegetation. A wide range of soil type and land-use combinations is sampled, but there is a bias toward those of greatest concern with regard to degradation.

Samples are collected for chemical, biochemical, physical and profile characteristics at each location (Sparling and Schipper 2002). Of the original soil properties measured, seven were selected for monitoring soil quality: soil pH, total C, total N, anaerobically mineralizable N, Olsen P, bulk density and macroporosity. These soil properties are combined into four primary factors describing soil quality: (1) fertility based on Olsen P, (2) acidity based on soil pH, (3) organic resources based on mineralizable N, total C and total N, and (4) physical status based on bulk density and macroporosity. The wide diversity in soil types and land uses in New Zealand contributed to the early recognition that the relation of soil properties to the fitness of soil for production and environmental objectives depends on soil type and land use (Manaaki Whenau Landcare Research 2004). Thus, for each of the seven soil properties retained for monitoring soil quality, response curves or target levels were developed by experts for different land use and soil order combinations, based on both environmental and production criteria (Manaaki Whenau Landcare Research 2004).

During development, a pragmatic approach was used to reduce the number of soil properties to a manageable level (Sparling and Schipper 2002). Measures that do not contribute to improved understanding for the goals of the program are dropped, although their potential value for other uses is indicated. For example, unsaturated hydraulic conductivity was dropped because high variability meant an impractical level of replication would be required to detect changes. Particle size distribution and CEC were dropped because they were not responsive to land use. Soil microbial biomass and soil respiration were dropped because these measures could not be interpreted, and because they were reasonably correlated with anaerobically mineralizable N. Base saturation was dropped because it was highly correlated with pH and it was more difficult to measure than pH. Total porosity was dropped because it was less responsive to land use than macroporosity and it was also inversely related to total C. The exclusion of certain measures was supported by observations and theoretical considerations that were relevant for conditions in

New Zealand. However, there is a danger that relevant information might not be obtained, particularly if a soil property is only important for specific land uses, soil types or soil functions.

Aggregation of soil quality information for regional assessment is ongoing (Manaaki Whenau Landcare Research 2004). However, quite a number of useful products are already available from this work. For example, web-based tools allow users to evaluate soil quality for their samples using the approach developed by the program (http://sindi.landcare.cri.nz/). Maps provide information on the vulnerability of different soils to various types of soil degradation and environmental risks, including structural degradation, acidification, N seepage, salinization, potassium deficiency, and microbial transport to shallow groundwater or waterways (McLeod 2003; Stephens et al. 2003; Manaaki Whenau Landcare Research 2004).

5.4 Europe Union

Countries within the European Union have made considerable efforts to develop agri-environmental indicators. In contrast to North America, most efforts have focused on environmental impact rather than on production, particularly for water quality as affected by excess nutrients or pesticide use. Another area of considerable interest in Europe is the conservation of agricultural lands for biodiversity, wildlife habitat and aesthetics. Examples of relevant agri-environmental indicators are provided in Table 4.

5.5 FAO

The Food and Agriculture Organization (FAO) and International Institute for Applied Systems Analysis (IIASA) developed an agro-ecological zoning (AEZ) methodology to assess potential sustainable food production, including meat and milk, at regional and national scales (Fischer et al. 1999). The methodology limits the type of agricultural land use to ensure that sustainability, environmental, social and economic goals are met. The methodology was first used in 1983 and has since been extended, refined and utilized at the sub-national and national scales in various developing countries. The methodology is based on the following principles that are considered fundamental to any sound evaluation of land resources:

- An interdisciplinary approach is required, with inputs from crop ecologists, pedologists, agronomists, climatologists, livestock specialists, nutritionists, economists, GIS specialists and sociologists.
- Land evaluation is only meaningful in relation to specific land uses.
- Suitable land uses must be sustainable, i.e., no degradation beyond tolerable limits in erosion, salinization, etc.
- Potential production depends on availability of agricultural inputs and technology.
- Different kinds of land use are required to meet demands for products.
- Different kinds of livestock feed resources may be suitable.
- Land use patterns must be constructed to optimize land productivity in relation to political and social objectives, taking into account physical, socio-economic and technological constraints.

Table 4. Examples of different types of agri-environmental indicators related to soil quality that are proposed or used in the European Union.

Type	United Kingdom	France	Germany	OECD*
Soil quality	Concentration of organic matter in topsoil Acidity Concentrations of certain heavy metals Soil management techniques	Number and intensity of severe incidents of soil erosion	Nitrogen balance	Risk of soil erosion by water and wind Mismatch between land capability and land use
Water quality	Trends in N use Nitrate and phosphate losses to freshwater Proportion of soils at different phosphate levels	Phosphate loading from fertilizers and effluents Average duration of cover crops Nutrient surplus of nitrates Contribution of agriculture to annual pollution by phosphates	Nitrogen balance Nitrate in soil in autumn and in leaching water Phosphate and pesticides in eroded matter Total erosion	Proportion of ground and surface water with high nitrate or phosphate levels Area of land potentially vulnerable to water contamination by nitrate and pesticides Quantity of water storage
Land use & conservation	Losses and gains of agricultural land	Land in agricultural use Progress in land planning		
GHG	Emissions of methane and nitrous oxides from agriculture	Emissions of methane, CO_2, and nitrous oxides from agriculture		
Biodiversity, habitat & landscape	Number of threatened species Number and diversity of bird, mammal, and butterfly species Area under commitment to environmental conservation Area under specific land uses	Number of threatened species Trends in wetland areas Areas under environmental protection	Biodiversity indicator (five criteria based on estimated value for natural species)	Area covered by semi-natural agricultural habitats Key species indicators
References	(Baldock 1999)	(Baldock 1999)	(Dabbert et al. 1999; Meudt 1999)	(OECD 1998)

*Organisation for Economic Co-operation and Development

The basic approach of this methodology is to describe both the requirements for different land uses and land attributes, and then to match them in order to determine suitable crops and potential productivity. Multiple land use types are considered. Land attributes are based on (1) climatic factors, (2) internal soil properties (temperature regime, moisture regime, fertility, effective depth, pH, EC), and (3) external soil properties (soil slope, occurrence of flooding and soil accessibility).

The methodology has other components. Maximum biomass production is determined based on climatic conditions, and attainable yields are based on the expected yield losses due to soil and management factors. Algorithms are used to eliminate land uses that are ecologically unsuitable, too risky, environmentally unacceptable or much inferior to other suitable land uses. The methodology also includes algorithms to assess livestock systems. Inputs for the method are obtained from available databases, models and expert opinions. Outputs of the method are estimates of potential, sustainable and acceptable levels of food production, which are obtained for a range of scenarios.

5.6 Overview

Table 5 summarizes differences among soil and land evaluation systems.

Objectives: The earliest systems of land evaluation were designed to provide extensive spatial coverage on land suitability for agricultural production or relative productivity (for taxation purposes). Due to increasing environmental and sustainability concerns, recent efforts in land evaluation are primarily designed to monitor land degradation over time.

Spatial scale: Most soil and land evaluation systems have a framework that is useful at large spatial scales, providing coverage at regional to national scales. However, evaluation systems for relative productivity or comparing land degradation among management practices were developed and are generally used within limited regions. The smallest resolution for assessment is at either the field or regional scale. Although all evaluation systems could theoretically be used at the field- or farm-scale, most serve their main purpose when used at regional or larger scales, and they may not be applicable at smaller scales because of insufficient data.

Complete coverage is achieved in most evaluation systems by assessing all land units. Some evaluation systems assess only a small fraction of land units based on statistical sampling (e.g., the National Resources Inventory in the United States) or benchmark sampling (e.g., New Zealand). Remote sensing techniques were not used in the soil/land evaluation systems reviewed in this paper, but they have the potential to increase the spatial coverage, resolution and/or integrated volume of assessments (Nizeyimana and Petersen 1998).

Temporal scale: Land suitability assessments are based on land and climatic variables that are slow to change, and therefore are valid for long time periods (e.g., >30 years). These assessments have only been conducted once in most cases. Evaluation systems to monitor land degradation are determined every one to five years, depending on data and resource availability. Simulation models are increasingly used to increase the integration volume and temporal coverage of assessments. For example, soil erosion models are used to estimate annual rates (increased integrated volume) of soil erosion for previous and future time periods (increased temporal coverage).

Table 5. Comparison of approaches to evaluate soil/land quality.

Primary objective	**Country & references**	**Spatial scale**	**Temporal scale**	**Multiple objectives**	**Multiple contexts**	**Inputs**	**Output**	**Output validation**
Land suitability and productivity	USA, Canada (Canada Land Inventory 1970; Helms 1992)	Field to national, 100% coverage	>30 y Single assessment	Built-in	Flexibility	Climate Landscape Stable soil properties	Simple classification system based on relatively simple algorithms	Fit with actual land use and erosion estimates
	Canada (Pettapiece et al. 1998)	Regional, 100% coverage	>30 y Single assessment	Built-in	Flexibility	Land use & management Climate Landscape Stable soil properties	Change in land suitability using model and simple algorithms	Based on data quality assessment, peer review, and model verification
	FAO (Fischer et al. 1999)	Regional to national, 100% coverage	>30 y, Single assessment	Built-in	Flexibility	Climate Crop Landscape Stable soil properties	Potential sustainable productivity based on model outputs	Based on model verification and data quality assessment
	USA (Huddleston 1984)	Field to regional, 100% coverage	>30 y Single assessment	Not applicable	Limited context	Climate Landscape Stable soil properties	Relative productivity based on simple algorithms	Fit with actual crop yields
Monitor degradation and environmental impacts of agricultural lands	USA (NRI) (Nusser and Goebel 1997; NRCS 2003)	Sub-state to national, 4% sample rate	Decades Assessment every 1 to 5 years	Dash-board	Context-independent indicators	Land use & management Climate Landscape Stable soil properties	Trends in many variables related to soil quality, based on simple algorithms and model outputs	Based on data quality assessment, peer review, and model verification

Primary objective	**Country & references**	**Spatial scale**	**Temporal scale**	**Multiple objectives**	**Multiple contexts**	**Inputs**	**Output**	**Output validation**
Monitor degradation and environmental impacts of agricultural lands (continued)	Canada (McRae et al. 2000)	Regional to national, 100% coverage	Decades Assessment every 5 years	Dashboard	Context-independent indicators	Land use & management Climate Landscape Stable soil properties	Trends in selected indicators related to soil quality, based on simple algorithms and model outputs	Based on data quality assessment, peer review, and model verification
	Europe (Brouwer 1995; OECD 1998)	Regional to national	Decades Assessment every 1 to 5 years	Dashboard	Context-independent indicators	Land use & management Climate Landscape Stable soil properties	Trends in selected indicators related to soil quality, based on simple algorithms and model outputs	
Monitor soil degradation	USA (among management options) (Karlen et al. 2001)	Field to regional, parametric sampling	Years to decades Variable assessment periods	Aggregated	Limited context, flexibility	Management-affected soil properties	Relative aggregated estimate of soil functional capacity	Based on responsiveness and peer review
	New Zealand (Sparling and Schipper 2002)	Regional to national, benchmark sampling	Decades Assessment every 3 years	Dashboard	Flexibility	Management-affected soil properties	Ratings of different aspects of soil quality	Based on data assessment and peer review

Multiple objectives: Methods to account for multiple objectives are necessary because factors contributing to the achievement of one objective may be negatively correlated to the achievement of other objectives. For example, nutrient availability is positively related to crop productivity and negatively related to water quality. Other factors may be related to multiple objectives in a similar way, but may have a greater impact on one objective than another. For example, soil erosion degrades both crop productivity and surface water quality, but tolerable levels of soil erosion may be lower for one objective than for the other. Three basic methods or approaches are used to account for multiple objectives of soils:

1) <u>Dashboard approach</u>: Multiple indicators are developed for different objectives or issues related to soil or land quality. For example, the current New Zealand system has four factors to describe the quality of a soil (fertility, acidity, organic resources, and physical status) and does not aggregate the factors beyond this level. The agri-environmental indicators system developed in Canada has six indicators describing the status of different soil degradation processes. This approach can often be shown using spider diagrams. The dashboard approach has considerable merit because more information is available from non-aggregated indicators, and appropriate aggregation of dissimilar or contradictory factors is extremely difficult to achieve.

2) <u>Aggregation approach</u>: In some situations, highly aggregated indicators are desirable. For example, communication to the general public through the media is improved using highly aggregated information because people do not have the time or interest to delve into the details of every issue (Jesinghaus 1999). Several approaches might be used to achieve this level of aggregation:

    a. Select one indicator to represent soil or land quality, e.g., the proposed use of trends in soil organic C as an indicator of soil quality, by the NRI in the United States (NRCS 2003).

    b. Select and weight multiple indicators using expert opinion (e.g., Karlen and Stott 1994).

    c. Obtain relative or absolute values (monetary or relative weighting) for all land outcomes (positive values for desirable outcomes, negative values for undesirable outcomes) and sum values for all outcomes of land management (Jaenicke and Lengnick 1999).

    Highly aggregated indicators are challenging to develop due to the requirements for valuation, output validation and communication. *Valuation* is the value or weight given to different components of the issue (e.g., productivity vs. environmental impact), and is strongly dependent on personal beliefs and values (Jesinghaus 1999). *Output validation* refers to the soundness of an indicator to supply reliable information on an outcome, but relations between proposed indicators and outcomes are difficult to ascertain with a high degree of confidence for large, complex systems. *Communication* of highly aggregated information for a broad audience is inherently more difficult than site- or issue-specific information to a limited audience of practitioners or industry stakeholders.

3) Built-in constraints approach: Information is provided for the objective of greatest interest, but the role of other objectives is built in by including constraints that affect the output from the primary objective. For example, in the FAO evaluation system, potential food production is limited by the objective to limit erosion rates by not allowing certain cropping systems on land that is susceptible to erosion (Fischer et al. 1999). An advantage of this approach is that linkages between different objectives are explicit and quantifiable. The major challenge for this approach is ensuring all the important objectives are appropriately included in the evaluation system.

Multiple contexts: Due to the large effects of crop type, technology, inputs and landform on potential crop productivity and environmental impact, these factors must be accounted for in any system designed to evaluate soil or land quality. Soil characteristics or management systems that lead to desirable outcomes (high crop productivity, low environmental impact) in a humid climate may not be beneficial in a semi-arid climate. Similarly, soil characteristics or management systems that lead to desirable outcomes for certain crops, landforms (e.g., hillsides vs. level land), or management strategies (e.g., low input vs. high input) may not be beneficial for alternative options. Several approaches have been used to account for the effects of these factors on soil or land evaluation systems:

- Limit the scope, or context, of the evaluation system. For example, many of the productivity indices are only designed for a specific crop in a specific geography.

- Design flexible systems. For example, desirable conditions for soil properties are defined for different land use types in the FAO system or for different land use/soil type combinations in the New Zealand system.

- Develop indicators that are less dependent on context, e.g., use trends rather than absolute values.

Inputs: The inputs used for soil/land evaluation systems reflect the purpose and scale of the objectives. Evaluation systems designed to assess land suitability are based on the most important factors controlling crop growth that cannot be ameliorated by short-term measures. Thus, inputs for these systems include climate, landscape and stable soil properties that are obtained from extensive soil surveys and long-term climatic records. Evaluation systems designed to assess land degradation either utilize measurements of management-dependent soil properties or infer land degradation from known relations of land degradation to management, climate, landscape, and soil variables.

The difference between management-dependent soil properties and stable or inherent soil properties is not absolute. As mentioned previously, soil properties vary at temporal scales ranging from seconds to centuries and at spatial scales ranging from millimetres to hundreds of kilometres. Over a sufficient time period, practices that affect dynamic soil properties will also affect stable soil properties, and stable soil properties will change.

Soil functions depend on both stable and dynamic soil properties, and the decision to limit assessment to either stable or dynamic soil properties is primarily a product of objectives. For example, an objective to compare potential crop productivity at different locations will focus on stable soil properties (e.g., topsoil depth, pH, texture) because these can account for much of the difference in potential crop productivity, while dynamic soil properties (e.g., soil water or nitrate concentrations) would need to be monitored much more intensively. In comparison, an objective to compare potential crop productivity as affected by management practices that influence dynamic soil properties, such as irrigation or fertilizer addition, will focus on the dynamic soil properties affected.

Output: The output from soil/land evaluation systems consists of ratings or trends based on algorithms used for system inputs. In almost all cases, the output provides information of the outcome of soil functions. Algorithms range from simple (e.g., weighted average of several measurements) to complex (e.g., simulation model using daily time steps for many soil processes).

Output validation: Validation of the outputs from the evaluation systems is required to ensure that correct messages are being communicated. In many cases, it is very difficult to determine how well an evaluation system has been validated. Earlier evaluation systems for land capability and productivity were validated through use and improvement of the system until the experts developing the system considered outputs reasonable. Improvements were guided by actual observations of land use, land degradation and crop yields. Simulation models are increasingly used because they are more quantitative and less dependent on user assumptions, but considerable care is required to ensure that they are used for purposes, contexts and scales for which they were intended (Addiscott 1993). As far as possible, outputs from evaluation systems should be validated by comparison with relevant observations or related variables (Bockstaller and Girardin 2003).

6.0 Soil/Land Quality Indicators for Alberta

Several different approaches for developing soil/land quality indicators have been used in Alberta:

Land Productivity Indicator: The Land Productivity Indicator is the average annual yield of the six major crops grown in Alberta (Serecon Management Consulting Inc. 2000). An overall yield is determined by weighting the yields from different crops by average seeded area, which is determined for a specified period of time. The major advantage of this indicator is that it is easy to calculate. The major disadvantages are that only one goal (crop productivity) related to soil functions is considered, and the knowledge that crop yields are a product not just of soil properties, but also of climate, management, and landscape, has not been incorporated into this indicator. Improvement of this indicator might be possible by the use of algorithms to isolate the impact of soil properties on crop yields.

Land Suitability Rating System (LSRS): Pettapiece et al. (1998) estimated the change in soil quality for 15 ecodistricts in Alberta. The changes in soil quality were estimated from the change in LSRS ratings over 30 years, which were based on EPIC simulations of soil processes. This approach primarily reflects goals related to crop productivity, but it also provides direct estimates of the type and extent of soil degradation, which could be used to develop indicators for other goals related to soil functions. Further validation of this approach is necessary, particularly with regard to prediction of yields and soil degradation, possible importance of dynamic soil properties, and possible use of simpler models.

Agri-environmental indicators: The Canadian system of agri-environmental indicators is relevant to most goals for soil functions and has been applied to all agricultural lands in Alberta (McRae et al. 2000). Crop productivity is not dealt with directly, but indicators are provided for various aspects of land degradation that impact on crop productivity (e.g., risks of water erosion, wind erosion, soil compaction, salinization, and loss of soil organic carbon). Indicators for soil functions related to water quality require further development for use in Alberta; they have not been determined for any of the Prairie provinces.

Agri-environmental indicators are largely based on expected outcomes from management, climate, soil and landscape factors. Insufficient data and knowledge limit the usefulness of a number of the indicators, and all would benefit from further validation. These indicators are developed at spatial scales from ecodistrict to national, and are not valid for use at smaller spatial scales.

Soil monitoring indicators: Indicators based on periodic measurements of soil properties have been used to compare management practices (Karlen et al. 2001) and monitor changes in soil properties over time (Sparling and Schipper 2002). The soil quality monitoring study in Alberta is based on this approach, although indicators have not yet been determined (Cannon 2001). The major advantages of this approach are that it is based on actual observations of soil properties and it aims to evaluate soil quality with respect to all soil functions.

The major disadvantages of this approach are its relatively high cost and the difficulty in relating measurements of soil properties to outcomes of soil functions. One reason for this difficulty is that goals for outcomes of soil functions are not formulated. Instead, indices based on soil properties are formulated (generally with insufficient validation) and compared among management systems or time periods. Another reason for this difficulty is that outcomes of soil functions are not simply determined by soil properties, but also depend on climate, landscape and management. This issue has been addressed by restricting the context in which soil property indicators are validated, or by restricting the indicators to soil properties that have a relatively consistent and significant effect on soil function outcomes (e.g., soil organic matter). These solutions are valid, but the value of the approach is considerably reduced.

An alternative solution would be to develop indicators based on the outcomes of soil functions using available information and appropriate models. A successful implementation of this approach would be of considerable benefit for validation of indicators based solely on soil survey and census data.

7.0 Recommendations

The following steps, based on the approach outlined in Figure 3, are recommended for the development of useful soil/land indicators in Alberta:

1) **Identify and involve end users.** “Indicators cannot be developed without a clear context and purpose, in terms of the information to be transferred and the types of target users”

(Crabtree and Brouwer 1999). End users must be involved to ensure that selected indicators are effective at communicating the relevant messages. In particular, involvement is necessary to ensure that the goals for outcomes of soil functions are real, clear and practical. Early involvement is necessary for the design of useful indicators. Type, scale and level of aggregation are all functions of end user needs and wants. Feedback should be obtained on existing and prototype indicators before considerable efforts are expended in the development of new indicators.

2) **Formulate appropriate goals for outcomes of soil functions**. Goals will have to be formulated at several spatial and temporal scales, e.g., province-wide vs. field-scale goals, short-term vs. long-term goals.

3) **Understand which variables and relationships are most important in controlling outcomes.** This understanding should be expressed in mathematical models. Many different models are available for most goals related to soil functions, and the inclusion of different models is recommended to ensure that an optimum solution is obtained and to provide additional validation.

4) **Assemble relevant databases.** Databases consisting of observed outcomes and the variables controlling outcomes should be assembled from studies relevant to Alberta conditions. Possible sources of data include benchmark studies, long-term crop rotation studies, research trials, and outputs from reliable models. Substitution of missing data using validated models or proxy variables may be necessary in some cases.

5) **Test candidate indicators.** Candidate indicators for outcomes of each soil function can be obtained from previous studies or derived from appropriate models. Three basic questions must be addressed when testing candidate indicators (Bockstaller and Girardin 2003):

   a. Is it scientifically founded?
      Addressed through peer review and comparison of approaches (design validation).

   b. Does it inform about the reality? Is it realistic?
      Addressed through comparison with actual observations or output from reliable models (output validation).

   c. Is it useful? Does it improve decisions cost-effectively?
      Addressed through tests with end users and estimation of costs (end-use validation).

6) **Aggregate indicators.** Indicators for different goals should only be aggregated after they have been validated for individual goals. Aggregation first requires an assessment of the relations among goals. Indicators of outcomes that are negatively correlated need to be aggregated in a different way than indicators of outcomes that are positively correlated. Aggregation also requires an assessment of the relative value of the different goals. Failure to achieve goals might be of minor importance for some goals, but of great importance for other goals. Different end users may have highly divergent viewpoints on the importance of different goals. The aggregation of divergent goals is inherently difficult and may not be valid or necessary.

These recommendations for the development of useful indicators for soil quality may appear formidable. However, considerable information is available from previous efforts in this area, and further improvement based on a sound approach is likely to progress quite rapidly.

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